

NEW “EINSTEIN CROSS” GRAVITATIONAL LENS CANDIDATES IN HST WFPC2 SURVEY IMAGES

Kavan U. Ratnatunga, Eric J. Ostrander, Richard E. Griffiths, & Myungshin Im
Bloomberg Center for Physics and Astronomy,
Johns Hopkins University, Baltimore, MD 21218
kavan, ejo, myung, & griffith@mds.pha.jhu.edu

To be published Astrophysical Journal Letters of November 1 1995

Received June 26 1995

Accepted Aug 24 1995

ABSTRACT

We report the serendipitous discovery of “Einstein cross” gravitational lens candidates using the Hubble Space Telescope. We have so far discovered two good examples of such lenses, each in the form of four faint blue images located in a symmetric configuration around a red elliptical galaxy. The high resolution of HST has facilitated the discovery of this optically selected sample of faint lenses with small ($\sim 1''$) separations between the ($I \sim 25 - 27$) lensed components and the much brighter ($I \sim 19 - 22$) lensing galaxies. The sample has been discovered in the routine processing of HST fields through the Medium Deep Survey pipeline, which fits simple galaxy models to broad band filter images of all objects detected in random survey fields using WFPC2.

We show that the lens configuration can be modeled using the gravitational field potential of a singular isothermal ellipsoidal mass distribution. With this model the lensing potential is very similar, both in ellipticity and orientation, to the observed light distribution of the elliptical galaxy, as would occur when stars are a tracer population. The model parameters and associated errors have been derived by 2-dimensional analysis of the observed images. The maximum likelihood procedure iteratively converges simultaneously on the model for the lensing elliptical galaxy and the source of the lensed components. A systematic search is in progress for other gravitational lens candidates in the HST Medium Deep Survey. This should eventually lead to a good statistical estimate for lensing probabilities, and enable us to probe the cosmological component of the observed faint blue galaxy population.

Subject headings: cosmology:observations - gravitational lensing - surveys

1. INTRODUCTION

Einstein (1936) computed the gravitational deflection of light by massive objects and showed that an image can be highly magnified if the observer, source and the deflector are sufficiently well aligned. However, the angular resolution available then to ground based optical telescopes made him remark that “there is no great chance of observing this phenomenon”. Zwicky (1937) showed that “extragalactic *nebulae* offer a much better chance than *stars* for the observation of gravitational lens effects”.

Over the last decade a number of lensed QSO candidates were located in radio surveys and subsequently the associated lensing galaxies were optically identified (See Schneider, Ehlers and Falco 1992 for review). Huchra et al. (1985) discovered the “Einstein cross” at the center of the bright ($V=14.6$) galaxy 2237+0305, an object in the Center for Astrophysics redshift survey: this lens is considered unique because of the very low probability of alignment of a QSO within $0''.3$ of the center of a nearby ($z=0.04$) galaxy. With the refurbished WFPC2 optics on the Hubble Space Telescope (HST), we have now been able to start an optical survey for gravitational lenses centered on field galaxies in the magnitude range $I=19-23$, searching for background field galaxies which are lensed into components with magnitudes $I=23-27$.

The Medium Deep Survey (MDS) is an HST key project which relies exclusively on the efficient use of parallel observing time to take WFPC2 images of random fields which are several arcminutes away from the primary targets of other HST instruments (Griffiths et al. 1994). Similar observations have been made by the Guaranteed Time Observers (GTO) using WFPC2 in parallel mode, in conjunction with primary GTO exposures. The GTO parallel observations have been made available to all HST GTO teams. In addition to these two parallel surveys, a major ‘strip’ survey was performed (Groth et al. 1995) using the WFPC2 in primary mode.

For the study of galaxies in the parallel surveys (MDS and GTO), we exclude fields at low galactic latitude and those inside Galactic globular clusters or local group galaxies, where the data are dominated by stellar images. The Groth-Westphal ‘strip’ and other fields with both I and V observations are processed through the MDS pipeline as they become available via the HST archive after the one-year proprietary period. We fit simple galaxy models to images of all extended objects detected, using the maximum likelihood method for determination of the best-fit galaxy parameters (Ratnatunga et al. 1995). In view of the large number of fields, most of the processing is automated except for a manual stage to correct for errors in the detection and resolution of objects, and in the final inspection of the fitted models and residual images.

Serendipitous discoveries have always been a major potential of the Medium Deep Survey. Previous results from the MDS have focussed on the systematic measurements of stars and galaxies (see Griffiths et al 1995 for a summary and a bibliography for the MDS). Although an unusual object was discovered in the very first MDS image from WFPC2 (Glazebrook et al. 1994), this was probably a proto-galaxy in formation at $z = 0.7$ with superluminous starburst knots, rather than a gravitational lens as originally suspected. The observations presented in this letter represent the first discovery of a relatively new class of objects.

2. OBSERVATIONS

Prior to December 1993, the aberrated data from HST and WF/PC could not be used for the purposes of the present study. In cycle 4 of HST observations, from January 1994 to June 1995, the MDS and GTO parallel datasets have comprised about 35 and 15 independent high galactic latitude fields, respectively, with at least two WFPC2 exposures in each of the F606W(V) and F814W(I) filters for each field. These fields have all been processed through the MDS pipeline. In addition, there are about 30 and 70 fields in these surveys, respectively, for which one or both of the filters has only one exposure; in these latter fields, unbiased cosmic ray cleaning is a more difficult task, and processing of these fields is not yet completed.

The 42 arc min long Groth-Westphal strip (Groth et al. 1995) consists of 28 contiguous WFPC2 fields centered at $b = +60^{\circ}25$ and $l = 96^{\circ}35$. The observations, covering a total area about 120 square arc minutes, were taken between 7 March and 9 April 1994. They were obtained from the HST archive and calibrated, stacked and processed in exactly the same way as fields obtained for the HST Medium Deep Survey. A root-mean-square(rms) error image reflecting both the excluded cosmic rays and the flat field was created and used in the object detection and subsequent image analysis algorithms. Full details of the catalog and statistical analysis of the distributions of magnitude, color, half-light radius, axis ratio, and position angle and location will be described in other publications.

In order to search for serendipitous objects and to correct any errors in the automated object detection process caused by confusion of overlapping or very bright images, the fields have been examined by one of us (EJO) by eye. During this process, it was noticed that the I=19.7 elliptical galaxy (HST14176+5226) was flanked by four fainter images which were all at about the same magnitude and color and much bluer than the central elliptical which had a half light radius of $1''.2$ (see Figure 1). The companion objects ($V \sim 26$) were about

1''.2 and 1''.6 distant from the center of the elliptical galaxy along the major and minor axes respectively. Furthermore, the objects on the cross appeared to be arcs. This galaxy was thus clearly identified as a very strong gravitational lens candidate.

A second fainter ($I=21.8$) and smaller (half light radius 0''.2) elliptical galaxy (HST12531–2914) was discovered by one of us (MI) when inspecting the residuals of the maximum likelihood model fits to galaxies in a deep MDS field urz00. Since the faint companion objects ($V \sim 27$) are only about 0''.5 from the central elliptical, they had not been resolved as separate objects by the automated object detection algorithm.

The observed image configuration, magnitudes and colors are given at the top of table 1. The magnitudes of the components were computed using a 0''.3 square aperture, and corrected to total magnitudes assuming a point source. The magnitude of the elliptical is from the model fit. The offsets (X,Y) are in WFC 0''.1 pixels from the centroid of the respective elliptical galaxy.

3. THE LENS MODEL

In this letter we will limit the model analysis to gravitational lenses described by singular isothermal elliptical potentials (Kormann, Schneider & Bartelmann 1994) which provide a sufficiently accurate representation for our purposes. We adopt their definitions and notations in this letter.

Since we had already developed software for 2-dimensional ‘disk + bulge’ decomposition of MDS galaxy images, we used the same procedure with a slight modification to do ‘bulge + gravitational lens’ decomposition of the observed light distribution. This procedure iteratively converges simultaneously on the maximum likelihood model for the lensing elliptical galaxy and the source, so as to produce the observed lensing galaxy and the configuration of images from the lensed source.

For the light distribution of the elliptical, we used the seven parameters that we routinely use for the analysis of a galaxy image with a single component: local sky, location (x,y), total magnitude, half-light radius, axis ratio and position angle. The lensed source was defined by four parameters: location (sx,sy) relative to the elliptical, and intrinsic magnitude and half-light radius. Since the morphology of the source was very poorly constrained, it was assumed to be bulge-like with spherical symmetry. The lens is defined by the critical radius (ξ_0) and the axis ratio of the mass distribution. An optional parameter

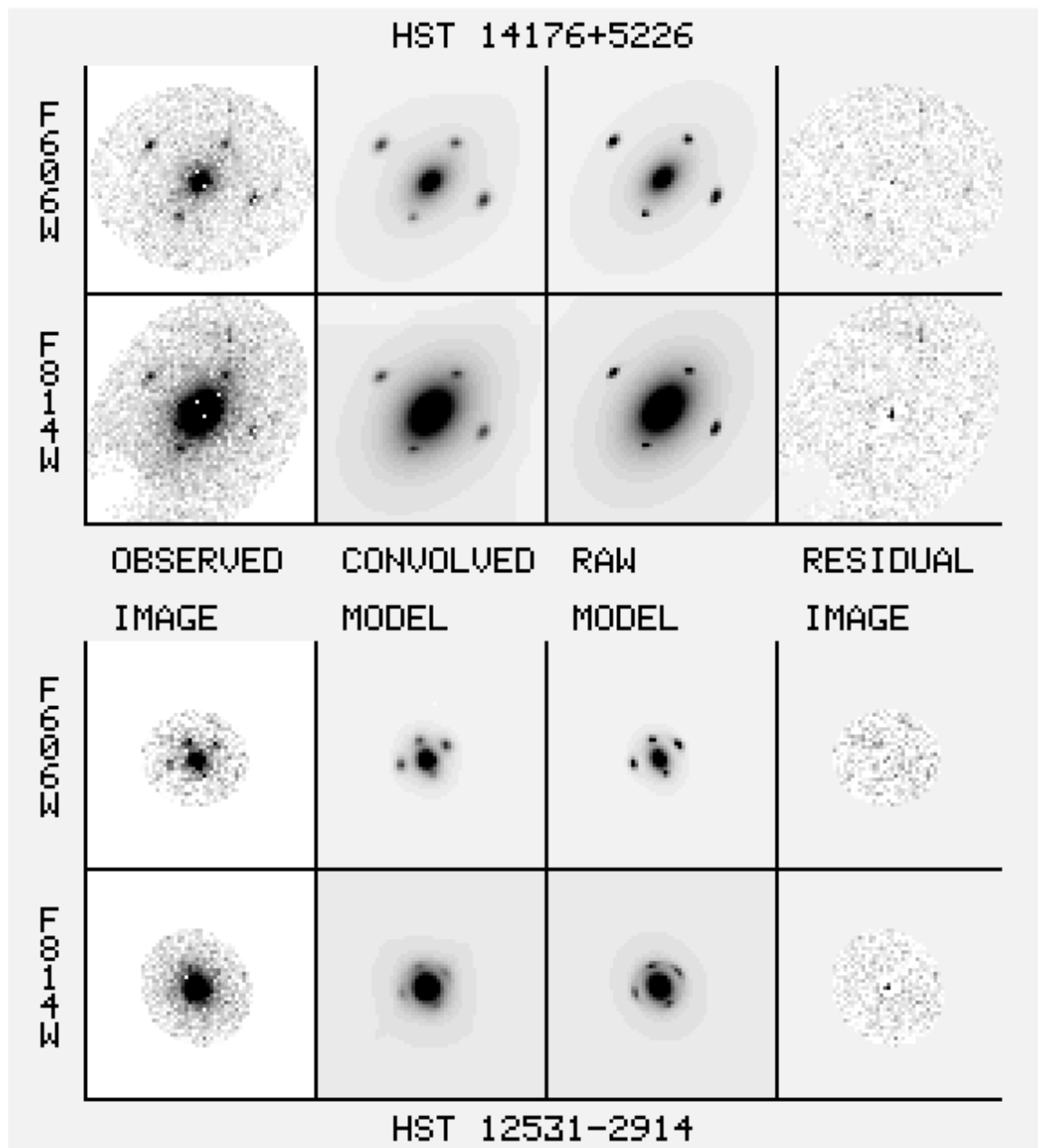


Fig. 1.— The maximum likelihood fits to the two gravitationally lensed images. The images are displayed as analysed, without any interpolation over bad pixels. Each box is $6''.4$ square. The residuals show only a very faint trace of the subtracted images. Note that the convolution with the WFPC2 PSF does influence the appearance of the lensed images.

is used to measure the difference in the orientation between the mass and the observed light of the lens.

Table 1: HST ‘Einstein Cross’ Gravitational Lens Candidates

Name	HST14176+5226						HST12531−2914					
Equ(J2000)	14:17:36.3 +52:26:44 V ₃ =32°93						12:53:06.7 −29:14:30 V ₃ =127°77					
HST WFPC2	Groth GTO:5090 11-Mar-1994						Griffiths GO:5369 15-Feb-1995					
Dataset[g][x,y]	U26X0801T[3][242,700]						U26K7G04T[3][755,326]					
Configuration	X	Y	V	±	V−I	±	X	Y	V	±	V−I	±
Elliptical	0	0	21.68	0.04	1.97	0.04	0	0	23.77	0.06	1.95	0.07
A	−11	11	25.63	0.06	0.51	0.10	−6	−2	27.02	0.15	0.25	0.28
B	18	−4	25.77	0.07	0.39	0.11	6	3	26.89	0.15	0.43	0.23
C	10	12	25.99	0.08	0.52	0.13	−2	4	26.72	0.11	0.34	0.21
D	−3	−9	25.97	0.08	0.42	0.14	3	−4	27.51	0.24	0.82	0.34
HST WFPC2 Filter	F814W		F606W		F814W		F606W		F814W		F606W	
Exposure seconds	4 x 1100		4 x 700		4 x 2100		3 x 1800		4 x 2100		3 x 1800	
Fitted Parameter	MLE	± rms	MLE	± rms	MLE	± rms	MLE	± rms	MLE	± rms	MLE	± rms
Sky Mag. (<i>arcsec</i> ²)	22.281	0.003	22.807	0.003	21.950	0.004	22.517	0.004	21.950	0.004	22.517	0.004
Total Mag of elliptical	19.71	0.01	21.68	0.04	21.82	0.03	23.77	0.06	21.82	0.03	23.77	0.06
X centroid 0′.1 Pix	242.41	0.02	242.28	0.03	754.83	0.02	754.78	0.03	754.83	0.02	754.78	0.03
Y centroid 0′.1 Pix	700.02	0.02	700.23	0.03	325.91	0.02	326.23	0.04	325.91	0.02	326.23	0.04
Half-light radius	1′′200	0′′006	1′′350	0′′058	0′′199	0′′013	0′′222	0′′023	0′′199	0′′013	0′′222	0′′023
Position Angle light	−37°8	0°8	−41°8	0°2	24°7	1°5	22°6	0°5	24°7	1°5	22°6	0°5
Axis Ratio of the light	0.68	0.01	0.65	0.03	0.84	0.03	0.73	0.07	0.84	0.03	0.73	0.07
Mag. of lensed source	25.76	0.2	26.1	0.2	27.4	0.2	27.4	0.2	27.4	0.2	27.4	0.2
Source X offset 0′.1 Pix	0.28	0.06	0.12	0.03	0.28	0.07	0.47	0.04	0.28	0.07	0.47	0.04
Source Y offset 0′.1 Pix	−1.24	0.07	−1.36	0.04	−0.23	0.09	−0.55	0.03	−0.23	0.09	−0.55	0.03
Critical Radius arcsec	1′′508	0′′008	1′′511	0′′005	0′′648	0′′010	0′′646	0′′006	0′′648	0′′010	0′′646	0′′006
Axis Ratio Lens mass	0.395	0.018	0.370	0.006	0.64	0.04	0.369	0.011	0.64	0.04	0.369	0.011
Source half-light	0′′016	0′′009	0′′018	0′′010	0′′053	0′′013	0′′031	0′′025	0′′053	0′′013	0′′031	0′′025
Lens Rotation	8°5	0°8	12°8	0°2	0°00	Fixed	0°00	Fixed	0°00	Fixed	0°00	Fixed

Given a set of model parameters, we generate 2-dimensional images for the elliptical and the source galaxies. The expected configuration of the lensed images is ray-traced by numerical integration. To improve the accuracy of the numerical integration, the image is evaluated using a pixel size smaller than the real one, such that the image fills a 64 pixel square array. The elliptical lens and the lensed source images are then convolved

with the adopted HST WFPC2 point spread function from TinyTim (Krist 1994). The convolved image is spatially integrated to the WFC pixel size of $0''.1$ and is then compared with the observed galaxy image. The likelihood function is defined as sum over all pixels of the logarithm of the probability of the observed value, assuming that it has a Gaussian error distribution with respect to the model. This is similar to a weighted χ^2 , and is then minimized using a quasi-newtonian method.

4. MAXIMUM LIKELIHOOD ESTIMATES

The results of the maximum likelihood estimates and errors are summarized in Table 1 and the corresponding images are shown in Figure 1 for both of the galaxies analyzed. The rms errors are estimated from the covariance matrix which is derived by inverting the Hessian at the maximum of the likelihood function. Note that the model parameters fitted independently to the F814W and F606W band images are very similar and well within the statistical errors and expected variations due to color. Since the fainter lensed images are blue and better resolved in F606W, the error estimates are smaller in this filter, even though the image exposure times in the F814W filter are 50% longer.

The critical radii of HST14176+5226 and HST12531+2914 are $1''.5$ and $0''.6$, in each case larger than the half light radii of $1''.2$ and $0''.2$ for these galaxies respectively. The lensed image components are more distant from the centroid of the lensing elliptical galaxy along the minor axis because the deflection is proportional to the gradient of the potential. The ratio in the distance between components at opposite ends of the cross is equal to the inverse axis ratio of the potential. The distance of the intrinsic source from the centroid of the lens needs to be less than about 0.15 of the critical radius for the creation of a quadruple image. The impact parameters for these two objects are about 0.08 and 0.09 of the critical radius.

In both cases the source has a half-light radius which is smaller than a WFC $0''.1$ pixel. However, the fact that the maximum likelihood estimate converged to a small but finite intrinsic source half-light radius appears to indicate that it is extended. We find such a value for the half-light radius to be similar to those of field galaxies at the magnitude of the lensed source (see Casertano et al. 1995, Im et al. 1995), i.e. within the range $0''.04 - 0''.40$.

A significantly better fit (99.9%) is obtained for HST14176+5226 by relaxing the constraint that the orientation of the lens mass is the same as that of the observed light. The difference is practically independent of the model used, and is $8^\circ 5 \pm 0^\circ 8$ in F814W and

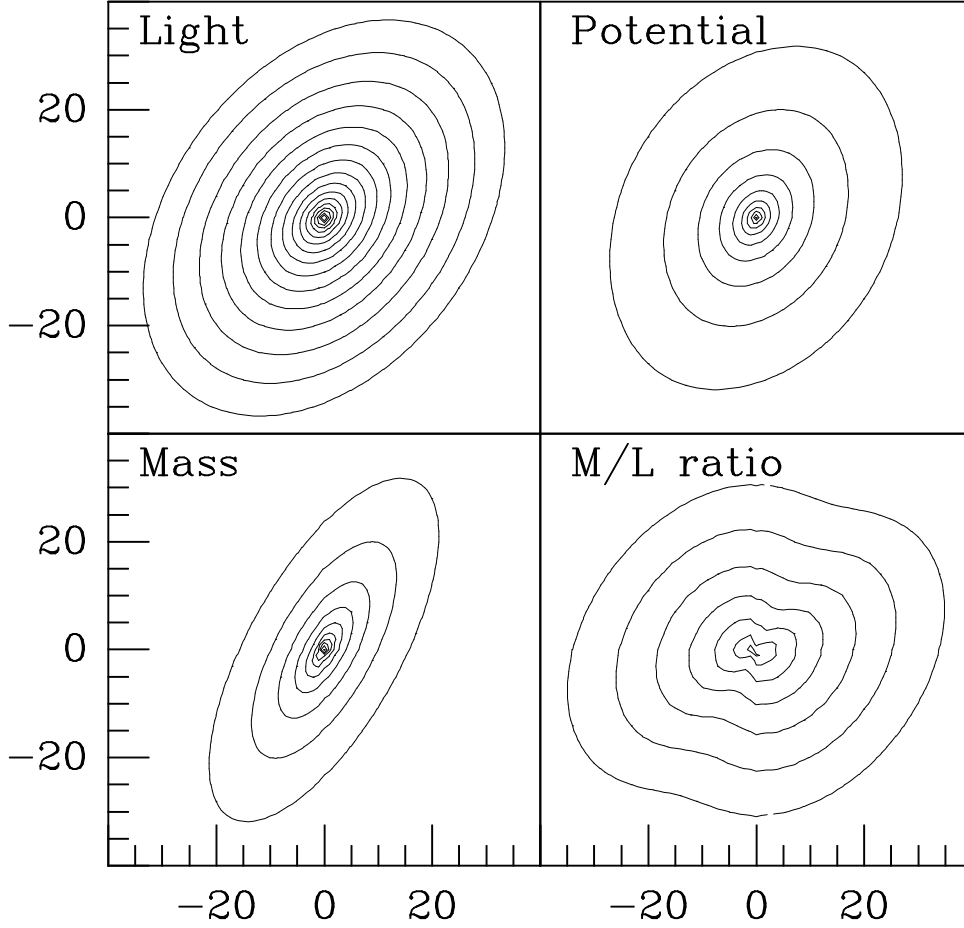


Fig. 2.— The observed light distribution of HST14176+5226, the maximum likelihood potential according to the elliptical mass model, and the resulting Mass/Light distribution, which is rounder (axis ratio=0.82) and increases radially outwards. All the contours have been drawn at constant 0.5 mag intervals, and units are $0''.1$ WFC pixels.

12.9 ± 0.2 in F606W. Such a small rotation might be expected from projection effects (see Franx, Illingworth & de Zeeuw 1991). As shown in Figure 2, the axis ratio (0.68) of the light from the elliptical galaxy HST14176+5226 is practically the same as that of the potential (0.74). The inferred elliptical mass distribution is significantly flatter than this (0.40).

Using the observed V–I colors, apparent magnitudes and half-light radii, we can estimate the redshift for each of the lens elliptical galaxies to be $z(D_d) = 0.7 \pm 0.1$ (see, e.g., Connolly et al. 1995). Using these redshifts, the luminosities of the elliptical galaxies can be estimated for the plausible range of evolutionary and K-corrections and the value of Ω , and thus the velocity dispersion v from the relation of Faber & Jackson (1976). We find

that the observed critical radii $\xi_0 = 4\pi(v/c)^2 D_d D_{ds}/D_s$, are more probable for $\Omega < 1$ for a source redshift smaller than $z(D_s) < 3$ (Guhatakurta, Tyson & Majewski 1990). For more detailed discussions, see Im et al. (1995).

5. CONCLUSIONS

We have discovered two examples of ‘Einstein-cross’ gravitational lenses in HST survey data, one in the MDS data and one in the archived Groth-Westphal GTO survey. The lens configurations show that the stars responsible for the light distribution of these elliptical galaxies are a trace population following the gravitational potential. The Mass to Light ratio increases radially outwards.

These represent the first discoveries of lenses using the high resolution of HST - indeed, apart from the exceptional original Einstein cross discovered by Huchra et al. (1985), they represent the first discoveries of field-galaxy gravitational lenses via the systematic study of optical images. They are a new class of gravitational lens candidates in which the cosmologically distant lens is a relatively bright elliptical galaxy with well understood properties. If a significant sample could be found and observed spectroscopically for redshifts, they will be very useful cosmological probes.

These objects would have been very difficult discoveries from the ground except under conditions of excellent seeing. Indeed, CCD frames taken at the KPNO 4m prime focus (Connolly 1995) do not show the cross objects flanking the elliptical galaxy HST14176+5226. We have not as yet observed these galaxies spectroscopically. The redshift of the lensed components in HST12531–2914 is probably a challenging observation for the Keck telescope in excellent seeing.

From the observed numbers of bright elliptical galaxies observed in the GTO survey strip (300 to I=22), the numbers of faint objects in the fields (8000 to I=26), and the expected cross-sections, we estimate that we should find one quadruple lens in every 20 – 30 WFPC2 fields surveyed. The number that has been discovered so far is therefore consistent with our expectations. An on-going systematic and careful inspection of the MDS fields, looking very specifically for possible gravitational lens candidates in the shallower MDS and GTO parallel fields is in progress in order to expand the sample. As further MDS data are taken in Cycle 5 and subsequent cycles, they will be examined for similar spectacular lenses, and also for more common lenses consisting of arcs or two or three components, to obtain a statistically representative sample of HST gravitational lens candidates.

This paper is based on observations with the NASA/ESA Hubble Space Telescope, obtained at the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS5-26555. The Medium-Deep Survey is funded by STScI grant GO2684. We gratefully acknowledge Lyman Neuschaefer for help with the MDS pipeline and many helpful discussions, the anonymous referee from many useful suggestions, and *et tu* Broadhurst.

REFERENCES

- Casertano, S., Ratnatunga, K. U., Griffiths, R. E., Im, M., Neuschaefer, L. W., Ostrander, E. J., & Windhorst, R. A. ApJ, 453, 000 (Nov 1)
- Connally, A., 1995, private communication
- Connolly, A., Csabai, I., Szalay, A. S., Koo, D. C., Kron, R. G., & Munn, J. A. 1995, AJ, submitted.
- Einstein, A. 1936, Science, 84, 506
- Faber, S. M. & Jackson, R. E. 1976, ApJ, 204, 668
- Franx, M., Illingworth, G. & de Zeeuw, T. 1991, ApJ, 383, 112
- Glazebrook, K., Lehar, J., Ellis, R., Aragon-Salamanca, A., & Griffiths, R. 1994, MNRAS, 270, 163
- Groth, E. J., Kristian, J. A., Lynds, R., O’Neil E. J., Balsano, R., Rhodes, J. 1994, BAAS, 26, 1403
- Griffiths, R. E., et al. 1994, ApJ, 437, 67
- Griffiths, R. E. et al. 1995, in Proc. IAU Symposium 168, “Examining the Big Bang and Diffuse Background Radiations”, Ed. M. Kafatos (Dordrecht: Kluwer), *in press*
- Guhatakurta, P., Tyson, J. A., & Majewski, S. R. 1990, ApJ357 L9
- Huchra, J., Gorenstein, M., Kent, S., Shapiro, I., Smith, G., Horine, E. & Perley, R. 1985, AJ, 90, 691
- Im, M., Casertano, S., Griffiths, R. E., Ratnatunga, K. U., & Tyson, J. A., 1995, ApJ, 441, 494
- Im, M., Ratnatunga, K. U., Griffiths, R. E. 1995, in preparation.
- Kormann, R., Schneider, P., & Bartelmann M. 1994, A&A, 284, 285
- Krist, J., 1994, ‘The Tiny Tim User’s Manual’, STScI

- Oegerle, W. R., & Hoessel, J. G., 1991, ApJ, 375, 15
- Ratnatunga, K. U., Griffiths, R. E., Casertano, S., 1995, in preparation.
- Schneider, P. Ehlers, J., Falco, E. E., 1992, Gravitational Lensing, Astronomy and Astrophysics Series, Springer-Verlag (SEF)
- Zwicky, F. 1937, Phys. Rev., 51, 290